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Evaluation of different turbine concepts for wind power

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Abstract

Every year the number of installed wind power plants in the world increases. The horizontal axis wind turbine is the most common type of turbine but there exist other types. Here, three different wind turbines are considered; the horizontal axis wind turbine and two different concepts of vertical axis wind turbines; the Darrieus turbine and the H-rotor. This paper aims at making a comparative study of these three different wind turbines from the most important aspects including structural dynamics, control systems, maintenance, manufacturing and electrical equipment. A case study is presented where three different turbines are compared to each other. Furthermore, a study of blade areas for different turbines is presented. The vertical axis wind turbine appears to be advantageous to the horizontal axis wind turbine in several aspects.

Keywords: VAWT; HAWT; Comparison; Darrieus; H-rotor; Evaluation

Contents

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1. Introduction

Wind power is an important source of environmental-friendly energy and has become more and more important in the recent years. The amount of installed wind power is increasing every year and many nations have made plans to make large investments in wind power in the near future. There are many different types of wind turbines and they can be divided into two groups of turbines depending on the orientation of their axis of rotation, namely horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs). The general public associates wind turbines with HAWTs and are unaware of the several other technologies based on the VAWT. The recent attention that VAWTs have received in several journals arouses an interest in making a comparative study between HAWTs and VAWTs [1–4].

This work aims at making a short historical background to wind power and then present a comparative study between HAWTs and two types of VAWTs. A case study is also presented where three 500 kW turbines are compared. Furthermore, a study of the blade areas of the different turbines is included. The paper does not give an overall review over wind power. For an overview of the current status of wind power, mainly focusing on HAWTs, see [5]. For an overview of wind turbine technologies with emphasis on HAWTs, see [6]. A review of the development of HAWTs and VAWTs can be found in Ref. [7].

1.1. Historical overview

The wind has been used as an energy source for a very long time, for example in sailing boats. The first windmills were used by the Persians approximately 900 AD [8]. These first windmills were VAWTs. During the Middle Ages, horizontal axis windmills were built in Europe and used for mechanical tasks such as pumping water or grinding grain. These were the classical four-bladed old windmills that had a yawing system and were mounted on a big structure. These windmills lost popularity after the industrial revolution. At about

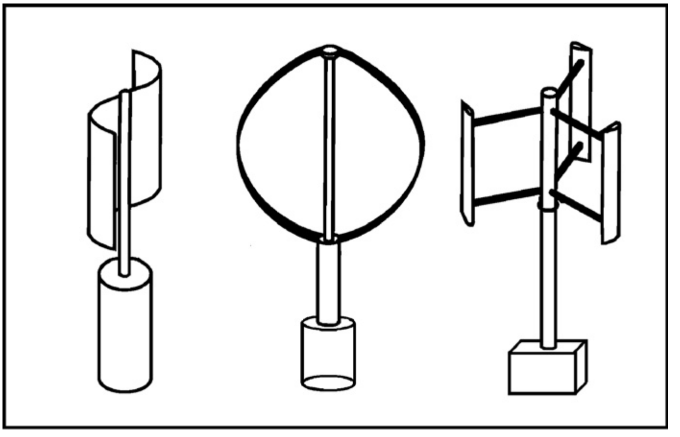

Fig. 1. To the left is a Savonius rotor, in the middle a Darrieus turbine and to the right an H-rotor.

the same time, water pumping windmills became popular in the United States, recognisable for their many blades and typically situated on a farm [8].

One of the first attempts to generate electricity by using the wind was made in the United States by Charles Brush in 1888. Among the most important early turbines was the turbine developed by Marcellus Jacobs. Jacobs' turbine had three airfoil shaped blades, a battery storage and a wind wane keeping the turbine against the wind. During the 20th century the HAWTs continued to evolve, which resulted in bigger and more advanced turbines, leading to the modern HAWTs [8].

Vertical axis machines have been developed in parallel with HAWTs, but with less financial support and less interest. The finish engineer S.J. Savonius invented the Savonius turbine in 1922, see Fig. 1 [2]. In 1931, Georges Darrieus patented his idea to have a VAWT with straight or bent blades, see Fig. 1 [9].

During the 1970s and 1980s vertical axis machines came back into focus when both Canada and the United States built several prototypes of Darrieus turbines. The prototypes proved to be quite efficient and reliable [2]. According to a report from Sandia National Laboratories in the USA, the VAWTs fell victims to the poor wind energy market in the USA [10]. The last of the Sandia VAWTs was dismantled in 1997 after cracks had been found on its foundation. In the 1980s the American company FloWind commercialised the Darrieus turbine and built several wind farms with Darrieus turbines [11]. The machines worked efficiently but had problems with fatigue of the blades, which were designed to flex [12]. The Eole, a 96 m tall Darrieus turbine built in 1986, was the largest VAWT ever built with a rated maximum power of 3.8 MW [13]. It produced 12 GWh of electric energy during the 5 years it was running and reached power levels of up to 2.7 MW. The machine was shut down in 1993 due to failure of the bottom bearing.

The straight-bladed VAWT was also an invention included in the Darrieus patent [9]. This turbine is usually referred to as the straight-bladed Darrieus turbine or the H-rotor, but has also been called giromill or cycloturbine (different concepts of the same invention) (see Fig. 1). In the United Kingdom, the H-rotor was investigated by a research team led by Peter Musgrove [2,14,15]. The biggest H-rotor built in the UK was a 500 kW machine, which was designed in 1989 [16]. In the 1990s, the German company Heidelberg Motor

GmbH worked with development of H-rotors and they built several 300 kW pototypes [17,18].

From this short historical review, it is clear that the first windmill was a VAWT but that later HAWTs received most attention. Could it be that it was only a coincidence that some researchers decided to develop the HAWT and that the VAWT only suffered from lack of interest? Brothers [19] claims that the HAWT is not obviously better than the VAWT just because it long ago was randomly picked for large-scale development.

Another discipline where the choice between vertical and horizontal axis turbines is fundamental is tidal current power conversion. For tidal current power vertical axis turbines are in favour in research projects conducted in several countries [20].

1.2. Commercialising VAWTs

There are several companies that market commercial products based on VAWT technology. The Canadian company Sustainable Energy Technologies sells a Darrieus turbine with a rated power of 250 kW called the Chinook 2000 [21]. Two research teams, that work with a geometry somewhere between the Darrieus turbine and the H-rotor are currently commersialising their products. The first turbine is from Netherlands and is called Turby [22,23] and the second turbine is Russian and is called Wind-Sail [24]. One of the established companies is Solwind Ltd. This company from New Zeeland manufactures and sells two-bladed H-rotors with a rated power of 30 kW [25]. Another company is Ropatec, which sells turbines with a rated power of 6 kW and a cut in wind speed of 2 m/s [26]. This Italian company uses a two-bladed H-rotor with big blades and an extra aerodynamic structure in the rotor centre. A worldwide market has been addressed. The German company, Neuhäuser, has developed a VAWT of the H-rotor type and has installed one turbine on a rooftop in Munich. Their largest turbine has a rated power of 40 kW [27]. Several other companies are currently working with a technology similar to the H-rotor [28–32].

1.3. Theoretical background

The amount of power, P, that can be absorbed by a wind turbine can be found from

$$P = \frac{1}{2} C_P \rho A v^3,$$

where C_P is the power coefficient, ρ is the density of the air , A is the swept area of the turbine and v is the wind speed. The power coefficient represents the aerodynamic efficiency of the wind turbine and is a function of the tip speed ratio, λ, which is defined as

$$\lambda = \frac{\omega R}{v},$$

where ω is the rotational frequency of the turbine, R is the turbine radius and v is the wind speed.

The solidity, σ, states a relation between the blade area and the turbine swept area and has different definitions for different types of turbines. For a HAWT, it is defined as

$$\sigma = \frac{Bc}{\pi R},$$

Table 1
Summary of the most important differences between the three turbines

	H-rotor	Darrieus	HAWT
Blade profile	Simple	Complicated	Complicated
Yaw mechanism needed	No	No	Yes
Pitch mechanism possible	Yes	No	Yes
Tower	Yes	No	Yes
Guy wires	Optional	Yes	No
Noise	Low	Moderate	High
Blade area	Moderate	Large	Small
Generator position	On ground	On ground	On top of tower
Blade load	Moderate	Low	High
Self starting	No	No	Yes
Tower interference	Small	Small	Large
Foundation	Moderate	Simple	Extensive
Overall structure	Simple	Simple	Complicated

where B is the number of blades, c is the chord length, and R is the radius of the turbine. For a VAWT, the solidity is defined as

$$\sigma = \frac{Bc}{R}.$$

2. Comparative study

The wind turbines considered here are the HAWT (propeller type) turbine, the Darrieus turbine and the H-rotor. A comparative study of the three wind turbines is presented from the most important aspects including structural dynamics, control systems, maintenance, manufacturing and electrical equipment. The main differences are summarised in Table 1 and are discussed in the following paragraphs. In several aspects, the similar characteristics of the Darrieus turbine and the H-rotor allow them to be referred to together as VAWTs. For other aspects the H-rotor and the Darrieus turbine are compared to each other.

2.1. Design

2.1.1. Yaw mechanism

The main difference between VAWTs and HAWTs is the VAWT's ability to accept wind from any direction, i.e. it is omni-directional. This has several advantages. The turbine does not require a yaw system, which is costly and could fail during operation. The yaw system includes both a control system and a drive mechanism. The costs associated with such a system include the cost of the equipment itself, installation cost and costs for operation and maintenance. Furthermore, with an omni-directional turbine there are no power losses during the time it takes for the turbine to yaw or during short wind gusts with temporary changes in wind direction [33]. Additionally, no power is lost to run the yaw system.

An omni-directional turbine can be situated at places where the wind is turbulent and where the wind direction changes often. For this reason, VAWTs have an advantage over HAWTs in high mountain areas, in regions with extremely strong or gusty winds and in urban areas [3]. Investigations indicate a clear advantage in using VAWTs at rooftops [23]. Furthermore, the VAWT is less noisy than the HAWT, which becomes even more important in urban areas [3]. Roof mounted VAWTs have been proposed as part of the energy source for the Freedom Tower in New York City [4].

2.1.2. Axis direction

The vertical rotational axis of a VAWT allows the generator to be located at the bottom of the tower. This makes installation, operation and maintenance much easier. The tower can be lighter for a VAWT since the nacelle is excluded, which reduces structural loads and problems with erecting the tower [19]. The generator design can be focused on efficiency, cost and minimising maintenance, as the size of the generator is not the main concern. Furthermore, the control system can also be located at ground level facilitating access [33].

2.1.3. Direct drive

Direct drive here denotes a solution where the turbine is directly, through a shaft, connected to the rotor of the generator. By using a direct drive generator, the gearbox is excluded from the system. A gearbox is often associated with breakdown and need of maintenance [34]. Furthermore, a direct drive system is much more efficient than a generator with a gearbox, since the gearbox is a source of losses comparable to the losses in the generator. The overall system, when excluding a gearbox, is simpler and it is easier to install. When directly coupled, the wind turbine will be able to react faster to changes in the wind and the load. Furthermore, the direct drive reduces the torsional constraints on the drive shaft imposed by eigen frequency oscillations and thereby enables the shaft to be slimmer than if a gear box had been used, which for an H-rotor means that the supporting tower mass also can be reduced [35].

Since a direct drive machine is more bulky and has a larger diameter than a conventional generator there are advantages by using a vertical axis turbine with a direct drive generator and placing the generator on the ground, where the size is not an issue. There are several companies that work with direct drive generators for HAWTs for instance Enercon, Germany's market leading manufacturer of wind turbines [36].

2.1.4. Construction

The blades of a HAWT have to be self-supporting since they are only attached at the root. The blades of an H-rotor are supported by support arms, which usually are attached to the centre of the blades. However, the support arms add extra structure and mass to the turbine.

The blades of an H-rotor are much easier to manufacture than the blades of a HAWT or of a Darrieus turbine. The blades of the two latter have different shape along the length of the blade and the blades might also be twisted. The Darrieus turbine has curved blades, which are complicated to fabricate and to transport [37]. These features make the manufacturing process much more complicated. The blades of an H-rotor have the same shape along the length of the blade and are not twisted but do sometimes have a reduced chord at the end points. The blade area is often larger for an H-rotor than for a HAWT with the same rated power, even though the blade areas could be the same as shown later.

For a larger blade area, more material is used. Mass production of H-rotor blades would imply low production costs since their shape makes them easy to fabricate in large numbers compared to HAWTs [19].

Sometimes it is claimed that VAWTs do not have a tower and therefore are situated close to the ground where the wind is low and turbulent. This is not generally true. The Darrieus turbine is indeed situated close to the ground, and has a long shape, which makes the wind shear noticeable. The H-rotor is normally placed on top of a high tower, just as the HAWT, in order to reach higher and less turbulent winds.

Guy wires could be used to support the shaft of a turbine since it gives a stiffer, more robust construction. The exterior supporting tower could then be excluded. HAWTs can not have guy wires that support the whole structure since they would interact with the turbine. The Darrieus turbine normally requires guy wires. Guy wires are optional for H-rotors, which is an advantage since guy wires are preferred in some cases but not for others, such as offshore or in heavily farmed areas.

HAWTs can have problems with tower interference caused by the tower shadow. This problem is not as big for upwind turbines as for downwind turbines. The tower shadow affects the turbine dynamics, gives power fluctuations and increases noise generation [8]. VAWTs do not experience tower interference as the distance between blades and tower is much larger.

A Darrieus can be built with a simple foundation compared to the other two turbines since it does not have a tower. The H-rotor has to have a moderate foundation whereas a HAWT needs an extensive foundation since most of its mass, including the whole drive train, is on top of the tower.

2.1.5. Structural mechanics

The blade of a HAWT is subject to a gravity-induced reversing stress at the root of the blade, which is not the case for VAWT blades [38]. This is believed to be the main limitation for increasing the size for HAWTs [2,14]. The blades of a HAWT are also subject to periodical loads due to the wind shear. These loads could cause fatigue of the blades [8]. The blades of the H-rotor are subject to large bending moments due to the centripetal acceleration [39]. The H-rotor suffers from larger bending moments than the Darrieus due to its long, straight blades [40]. This effect decreases as the turbine size increases since the centripetal acceleration decreases with increasing turbine radius, assuming a constant blade speed.

HAWTs have relatively constant torque. VAWTs have an inherent torque ripple [19]. The torque ripple is caused by the continuously changing angle of attack between the blades and the apparent wind. The torque ripple can affect the fatigue life of the drive train components as well as the output power quality [41]. By increasing the number of blades to three or more, the torque ripple is decreased substantially [42]. Furthermore, the problem with torque ripple is decreased when the turbine is operated at variable speed [19]. The aerodynamic forces on the blades caused by the changing angle of attack will also cause a cyclic aerodynamic stress on the blades. Some of the machines built in the 1970s and 1980s suffered fatigue damage of the blades, due to the cyclic aerodynamic stresses on the rotating blades [43]. However, these blades were made of aluminium, today replaced by composite blades with better fatigue properties [43]. The fatigue of past designs does not depend on the VAWT technology as such, rather on the limitations in modelling the

behaviour of a VAWT turbine and in building strong blades. With modern material and a thorough evaluation of the loads, problems with fatigue of the blades can be avoided.

2.1.6. Size

A trend in wind power development has been to increase the size of the turbines. In addition, the interest for off shore wind power has increased. For off-shore applications, the foundation and installation costs are so high that it becomes more economical with larger turbines [14]. Steven Peace, director of the company Eurowind Developments Ltd. [31], believes in multi-megawatt VAWTs [12,44], which was suggested by Musgrove 20 years ago [14]. They both claim that HAWTs have reached their maximum size and that the size will not be of economic benefit anymore [2,14]. The reason for this is the cyclically reversing gravity loads on the blades, which increases with an increasing turbine size. For VAWTs there are no such limit and therefore VAWTs are a good replacement for the HAWTs as the size of the turbines are expected to continue increasing [12,14].

On the other hand Riegler finds the biggest value in small VAWTs [3]. He claims that HAWTs are so economical they might be hard to beat when it comes to big turbines, but that small VAWTs can play their role in areas where HAWTs do not work that well for example in mountain areas or in regions with extremely strong and gusty winds, for instance roof tops.

2.2. Aerodynamics

2.2.1. Performance

The performance of a wind turbine depends on the power coefficient, C_P, which states how much of the power in the wind that is absorbed by the wind turbine. The theoretical maximum power coefficient is called the Betz limit and is 0.59 for an idealised wind turbine [8]. For a HAWT, the C_P value is usually between 0.40 and 0.50 [45]. It is difficult to state the exact value of C_P for VAWTs since there are few turbines operating. Values of C_P are therefore based on theoretical studies and on experimental results from different studies and are usually around 0.40. In 1987, Musgrove stated that extensive experimental and theoretical studies had shown that VAWTs had an efficiency comparable with the best modern HAWTs [14]. During the last 20 years, the HAWT technology has developed further, which implies that VAWTs could develop in the same direction if money and time was invested in research. Most known C_P values for VAWTs are 20–30 years old. Important progress in material and aerodynamic research has been made since then, which could increase the performance.

Power curves for the three different turbines can be seen in Fig. 2. The power coefficient, C_P, is shown as a function of the tip speed ratio, λ. The curves are based on data from different sources. The H-rotor is the British VAWT 260, which is a 100 kW, two-bladed turbine [15]. The data for the Darrieus turbine come from the turbine Sandia-34, a 500 kW turbine, developed and tested by Sandia National Laboratories [46]. The data for the HAWT come from the National Renewable Energy Laboratory in the USA and is claimed to represent data for a typical HAWT [45]. Fig. 2 indicates that the three turbines operate at different optimum tip speed ratios, which affects the noise level. The VAWTs have almost as good efficiency as the HAWT. The higher C_P value for the HAWT can to some extent be explained by the considerably greater experience of HAWTs, which has given a more optimized design. The Darrieus turbine is known to have a lower C_P than the

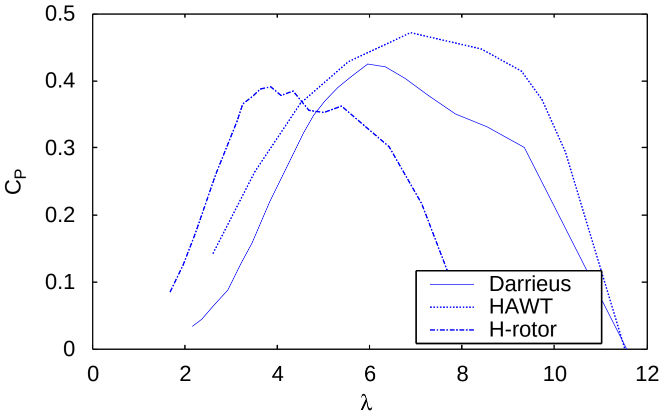

Fig. 2. Power curves for the three different turbine types.

Table 2
Experimental results from different studies on H-rotors

$C_{P,\max}$	λ (at $C_{P,\max}$)	Rated power (kW)	Country	Year
0.40	3.8	100	Great Britain	1989
0.38	4.3	Not stated	USA	1980
0.39	5.5	~2–4	USA	1979
0.38	4.4	14	Japan	1984
0.43	3	1	USA	1979

HAWT. However, Paraschivoiu claims that the gap between the C_P of a Darrieus turbine and a HAWT is not great and that the performance of the Darrieus can be improved by using airfoils that reduce drag [40].

Roynarin et al. have studied power curves for a prototype of an H-rotor and their test results are promising [33]. Their theoretical results predict a maximum C_P of 0.54 at a tip speed ratio of 2.5 for a small H-rotor. The investigation made by Ågren et al. [42] also shows very promising results for the performance of the H-rotor. Their high theoretical C_P makes the authors question if the Betz limit is the upper limit of the power coefficient for VAWTs. Mertens et al. have showed that the power coefficient of an H-rotor is higher than the power coefficient of a HAWT when the turbine is placed on a rooftop [23].

Experimental results from different studies on straight bladed H-rotors are summarised in Table 2 [15,39,47–49]. Walters et al. [47] conclude that their results shown on line 3 in Table 2 are encouraging and could be improved. They suggest several possible improvements of their turbine, among others to improve the blade profile and to optimise the blade angle and turbine solidity.

HAWTs are self-starting at a low wind speed. VAWTs have poor starting torque due to the blade stall condition at high angles of wind attack [37]. The H-rotor has better self-starting ability than the Darrieus turbine [50]. For a grid connected turbine, the grid can be used to start the turbine by using the generator as a motor [51] and therefore the self-starting is not a major issue. However, there are examples of self-starting VAWTs [3].

2.2.2. Power control

It is imperative to control the amount of power extracted from the wind and to be able to stop the turbine at high wind speeds. Most HAWTs use pitch control or active stall control. This requires a complicated control system as well as a mechanical system that turns the blades out of the wind. For a Darrieus, it is not possible to control the power using pitch control [50]. One of the pioneers in VAWT technology, Peter Musgrove, invented a variable geometry VAWT where the blades could be folded in high wind speeds, avoiding over speeding of the turbine. In the following projects, this technology was abandoned for a stall regulated, fixed speed geometry [2]. Means of power control is optional for the H-rotor. In order to simplify the structure passive stall control is preferred. A control system keeps the rotational speed constant at its rated value for wind speeds above rated wind speed. For increasing wind speed, the tip speed ratio will decrease, the blade will start to stall and thereby reduce the absorbed power. A mechanical brake, as a complement to the electrical or aerodynamic break, is desired in most cases. For a VAWT, a mechanical brake can be placed at the bottom of the tower.

2.3. Environment and noise

When guy wires are used to support the wind turbine, more ground area is covered [19]. However, space can usually be found since wind turbines preferably are built where the land is flat and far from buildings. Furthermore, a security distance from roads or buildings is required anyhow, especially if icing needs to be considered. In farmed areas, this could become a problem [51].

The H-rotor is expected to produce much less noise than a HAWT. There are two main sources for wind turbine noise; aerodynamic noise from the turbine's blade tips and mechanical noise from the drive train components. The aerodynamic noise increases with increasing blade tip speed of the turbine [8]. A VAWT usually has a tip speed which is approximately half the tip speed of a HAWT and it therefore produces less aerodynamic noise [52]. Since a VAWT has the drive train components at ground level, the possible noise from these parts will not propagate as easily as when the drive train components are situated on top of the tower [19]. The Darrieus turbine rotates faster than the H-rotor but slower than a HAWT of the same size. It will therefore produce more noise than the H-rotor but less noise than the HAWT. The VAWT 260 is from field experiments experienced to be very quiet in operation [15].

The H-rotor is expected to be less harmful for birds and bats, since the blades move at a slower pace and the speed of the blade has been shown to affect the risk for collision greatly [53]. Furthermore, problems with icing are less severe with a VAWT compared to a HAWT and less security distance is required. This is due to the lower rotational speed of a VAWT but also since an ice part that comes loose cannot get a velocity directed upwards when leaving a VAWT, as could be the case with ice parts leaving a HAWT blade.

2.4. Cost

The overall cost of a wind turbine is determined by the manufacturing costs, the amount of captured energy, the cost for site preparation and installation, the maintenance cost and the financing cost [40]. When comparing the manufacturing costs of VAWTs and HAWTs, it must be considered that the HAWTs have been produced for a long time and are

produced in large numbers. The time aspect gives smarter and cheaper solutions and the large numbers presses the prices down since parts can be mass produced. Furthermore, as the technology has matured it has been possible to scale up the HAWTs, lowering the cost per installed kW even more. No mass production of VAWTs exists.

The cost for a wind turbine is measured in cost per generated energy, cost/kWh. The generated energy for a specific turbine depends on the efficiency of the turbine, which is measured by the power coefficient, C_P, and the efficiency of drive train, generator and grid connection. The difference in costs between VAWTs and HAWTs for planning, producing, transporting and erecting a turbine and for O&M is mainly governed by the different costs for producing the turbine and the costs for O&M with some exceptions; it might be easier to erect the lighter tower of a VAWT, and it might be easier to transport the shorter blades of a HAWT, whereas the curved blades for the Darrieus turbine is very difficult to transport.

The C_P for VAWTs is expected to nearly reach values of C_P for HAWTs [40]. The design of the H-rotor is based on simplicity. By omitting a yaw system and the heavy nacelle and by having straight blades, the production costs are lowered even though the H-rotor usually has longer blades than a HAWT. For a Darrieus turbine, the blades are expensive to manufacture since they are both long and bended and sometimes also twisted. The cost analysis made by Walters et al. [47] indicates that VAWTs could be cost competitive to HAWTs.

It is important to reduce the cost associated with operation and maintenance in order to keep the total cost down. For the off shore market it becomes even more important to have a machine that needs as little maintenance as possible. This gives an advantage for the VAWT since it with its simple structure and few movable parts requires less maintenance than the HAWT do. Furthermore, a wind turbine with no yaw system, no pitch system and all electrical parts at ground level, can mostly be maintained from the bottom of the tower so no crane or climbing is needed. For a HAWT, most parts have to be maintained from the top of the tower.

3. Case study

The results from a case study of three different wind turbines can be seen in Table 3. The data in column 1 (H-rotor 1) are based on data for the VAWT 850 [16,54], a 500 kW VAWT constructed in UK, which started rotating in 1990. This machine has a generator and gearbox at the top of the tower, secluded by the tower. In column 2 (H-rotor 2) a design has been proposed that combines the turbine from the VAWT 850 machine with a slimmer tower including a vertical shaft connecting the turbine to a direct drive generator situated at the bottom of the tower. The advantages with direct drive have been discussed earlier. The weight of the tower is thereby reduced substantially. The data in column 3 (Darrieus) comes from a 500 kW Sandia turbine built in the late 1980s [46]. The data for the Darrieus turbine weight come from [40]. In column 5 (HAWT), data are presented from a commercially available 600 kW HAWT produced by Siemens [55]. In column 4 (HAWT scaled), the data from column 5 has been scaled down, using Froude scaling, in order to be valid for a 500 kW turbine [56].

When analysing these figures, it is important to notice that the swept area and the rated wind speed are different for the different cases. Also, the tower height is lower for the H-rotor. The H-rotor considered here has two blades. The number of blades for an

Table 3
A comparison of technical specifications for different turbines

	H-rotor 1	H-rotor 2	Darrieus	HAWT (scaled)	HAWT
Rated power (kW)	500	500	500	500	600
Swept area (m^2)	850	850	955	1370	1520
Rated wind speed (m/s)	~13.5	~13.5	12.5	15	15
No. of blades	2	2	2	3	3
Tower height (m)	30	30	50	47	50
Turbine diameter (m)	35	35	34	42	44
Blade length (m)	24.3	24.3	54.5	18	19
Blade material	GRP	GRP	Aluminium	GRP	GRP
Yaw mechanism	No	No	No	Yes	Yes
Pitch or active stall mechanism	No	No	No	Yes	Yes
Gear box	Yes	No	Yes	Yes	Yes
Guy wires	No	No	Yes	No	No
Generator position	In tower	On ground	On ground	In nacelle	In nacelle
Rotation speed (rpm)	Constant, 13.6/20.4	Variable	Semi-variable, 28–38	Constant, 19/28	Constant, 18/27
Overall structure	Simple	Simple	Moderate	Complicated	Complicated
Mass blades only (t)	6	6	-	13	15
Mass turbine (t)	~24	~24	72.2	13	15
Mass nacelle (t)	~20	No nacelle	No nacelle	20	23
Mass tower (t)	153	32.8	No tower	36	42
Total weight above ground level (t)	197	56.8	72.2	68	80

H-rotor is proposed to be three instead of two for a more even torque [42]. The Darrieus turbine has very long blades. The blades of the H-rotor are slightly longer than the blades of the HAWT.

The HAWT has both a yaw mechanism and an active stall regulation. This makes the overall structure more complicated. The generator and gearbox is placed in the nacelle and high up in the tower for the HAWT and H-rotor 1, respectively. For H-rotor 2, the generator is placed on ground level as for the Darrieus turbine. There are several advantages with having the generator at ground level as has been discussed earlier.

The blades for the H-rotor weigh less than the HAWT blades do. It should be noted that even though the turbine is designed for the same rated power, a larger swept area has been used for the HAWT. The blades of the HAWT have to be self-supporting whereas the blades for the H-rotor are supported by support arms and therefore can be built lighter. There is no figure for the weight of the blades of the Darrieus turbine alone, but the blades are expected to be very heavy since the turbine is heavy. The support arms for the H-rotors are made of steel and have large dimensions. Support arms could instead be made of a light but strong composite material and could have a slimmer structure. This would decrease the turbine weight for the H-rotor.

The mass of the tower for the H-rotors differs a lot. H-rotor 1 has a huge tower made of concrete whereas H-rotor 2 has a slimmer steel tower. The tower of H-rotor 2 does not have as much weight to support since the generator is placed on ground level. When

comparing the total weights above ground level for the different wind turbines it is shown that H-rotor 2 has the lightest weight above ground level. The weight of the generator is not included in this weight. When it is included the weight of H-rotor 2 is slightly larger than the weight of the HAWT. However, the weight of H-rotor 2 could be further reduced by the use of composite support arms. The weight of the Darrieus when including the generator and gearbox becomes much larger.

4. Blade area study

It is often argued that the turbine is more complicated and larger for a VAWT than for a HAWT. In particular, it is argued that the blade area is larger for a VAWT than for a HAWT. This is not necessarily true. The total blade area for a turbine depends on its solidity, which is dependent on the tip speed ratio, λ, of the turbine. In Table 4, blade area data for different turbines are shown. The Darrieus turbine has a height to diameter ratio of 1.25 and data are taken from [46]. A typical value for the solidity for a HAWT is between 5% and 7%, here 6% is chosen [57]. The values for solidity versus C_P and λ for the H-rotor is found in [40]. These data come from a Darrieus turbine with a height to diameter ratio of 1.0 but are expected to model the H-rotor fairly well. The blade area of the H-rotor is independent of the blade length to radius ratio for the H-rotor. The "blade area fraction" in Table 4, denotes the actual blade area divided by the blade area of the HAWT. The swept area and the number of blades are the same for all turbines.

As shown in Table 4, the blade area for an H-rotor does not necessarily have to be larger than the blade area for a HAWT. The size of the blade area is directly dependent on the tip speed ratio. The higher tip speed ratio, the lower solidity and thereby smaller blade area. Potentially, a low solidity could jeopardize the strength of the blade as the associated high tip speed ratio gives larger bending moments due to the larger centrifugal acceleration. However, as mentioned earlier the centrifugal acceleration decreases with increasing turbine size. From a structural point of view there is an upper limit for the tip speed ratio. The power coefficient, C_P, for the H-rotor, decreases as the solidity decreases. To some extent it might be worth having a lower C_P in order to decrease the amount of expensive material for the blades. This is a trade off that has to be settled in future development. Another disadvantage with reducing the blade area and thus increasing the tip speed ratio is that the turbine would produce more noise, as discussed earlier.

It should be noted that even though the blade area is the same for a HAWT and the H-rotor, the blade length is always longer for the H-rotor blade than for the HAWT blade. The difference in blade length depends on the blade length to radius ratio for the H-rotor and is between 1.25 and 1.77 for a length to radius ratio between 1 and 2.

Table 4
Blade area comparison for different turbines

Turbine	Tip speed ratio	$C_{P,\max}$ (theoretical)	Solidity	Blade area fraction
H-rotor	4	0.45	0.30	2.50
H-rotor	5	0.43	0.20	1.67
H-rotor	6	0.38	0.12	1.00
Darrieus	5.4	0.44	0.13	2.91
HAWT	5–7	0.47	0.06	1.00

5. Discussion and conclusion

Significant differences between wind turbines depending on the direction of their axis of rotation have been presented. This comparative study has shown that VAWTs are advantageous to HAWTs in several aspects. Furthermore, common misjudgements about VAWTs have been discussed. When comparing the two types of VAWTs considered here, the H-rotor seems more advantageous than the Darrieus turbine. The strength of the H-rotor concept is the possibility to keep the structure simple. The H-rotor does not require any yaw mechanism, pitch regulation or gearbox and therefore has few movable parts. Another advantage is its expected low need of maintenance.

A VAWT has been showed to work better than a HAWT in severe wind climates, for instance at a rooftop. It would be worth investigating if the VAWT could be an alternative to HAWTs considering large turbines for off-shore use, where the low need of maintenance makes the VAWT attractive. The HAWT is already established on the global market and it still has to be proven that VAWTs are an interesting alternative for wind power generation and more funding and interested researchers are needed to do so.

The case study presented a comparison between three turbines. Here, an example of an H-rotor that can be a competitor to HAWTs is presented. It has about the same weight as the HAWT but has a simpler overall structure. Some further simplifications of the suggested H-rotor have been proposed, for instance to make the support arms lighter. It has also been suggested that the H-rotor should have three blades instead of two.

The study of blade areas has shown that the argument that the blades of a VAWT are much larger than those of a HAWT not necessarily is correct. The blades of the H-rotor can be made even smaller than the blades of a HAWT but this might jeopardize the strength of the blades.

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